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Economic dispatch using particle swarm optimization: A review

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ABSTRACT

Electrical power industry restructuring has created highly vibrant and competitive market that altered many aspects of the power industry. In this changed scenario, scarcity of energy resources, increasing power generation cost, environment concern, ever growing demand for electrical energy necessitate optimal economic dispatch. Practical economic dispatch (ED) problems have nonlinear, non-convex type objective function with intense equality and inequality constraints. The conventional optimization methods are not able to solve such problems as due to local optimum solution convergence. Meta-heuristic optimization techniques especially particle swarm optimization (PSO) has gained an incredible recognition as the solution algorithm for such type of ED problems in last decade. The application of PSO in ED problem, which is considered as one of the most complex optimization problem has been summarized in present paper.

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1. Introduction

Economic dispatch problem has become a crucial task in the operation and planning of power system. The primary objective of ED is to schedule the committed generating units output so as to meet the required load demand at minimum cost satisfying all unit and system operational constraints. Improvement in scheduling the unit outputs can lead to significant cost saving. Initially, ED problem was formulated as economic cost dispatch (ECD), but further due to the amendment of clean air act in 1990s, existence of emission dispatch (EMD) leads to the formulation of combined emission economic dispatch (CEED) and emission controlled economic dispatch (ECED) problem formulation, as individual optimization of these two contradictory objective will not serve the purpose. Various conventional methods like Bundle method [1], nonlinear programming [2,3], mixed integer linear programming [4–7], dynamic programming [8], quadratic programming [9], Lagrange relaxation method [10], network flow method [11], direct search method [12] reported in the literature are used to solve such problems. Practically, ED problem is nonlinear, non-convex type with multiple local optimal point due to the inclusion of valve point loading effect, multiple fuel options with diverse

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equality and inequality constraints. Conventional methods have failed to solve such problems as they are sensitive to initial estimates and converge into local optimal solution and computational complexity. Modern heuristic optimization techniques proposed by researchers based on operational research and artificial intelligence concepts, such as evolutionary programming [13–16], genetic algorithm [17–21], simulated annealing [22–24], ant colony optimization [25,26], Tabu search [27,28], neural network [29–33], particle swarm optimization [34–67] provide the better solution. Each method has its own advantages and disadvantages; however PSO has gained popularity as the best suitable solution algorithm for such problems. This paper is a response note on previous work of application of population based PSO algorithm to solve the various ED problems.

2. Problem formulation

Economic dispatch requires a judicious formulation of practical ED problem. Talaq et al. [73] and Lamont and Obessis [76] suggested the various kinds of ED problem formulation. It can be formulated as single objective and multi-objective problem which are nonlinear and non-convex in nature. Single objective problem can be formulated as ECD without valve point loading effect [36,38,35,18,47,40], ECD with valve point loading effect (ECD-VPL) [34,31,52,37,55,49], ECD with valve point loading effect and multiple fuel option (ECD-VPL-MF) [39,41,49,53], EMD and ECED [73,78,77,56,79]. Multi-objective formulation includes combined emission economic dispatch CEED [77,44,60,45,56,57,54], multi-area emission economic dispatch MAEED [42,43], power generation under different utilities [69], maximization of generated power and irrigation [31].

2.1. Objective function

The primary objective of any ED problem is to reduce the operational cost of system fulfilling the load demand within limit of constraints. The various kinds of objective function formulation are given below.

2.1.1. Single objective problem formulation

Single objective ED problem can be formulated as fuel cost function (A)–(C) or emission of green house gases (D) as an objective function. The fuel cost and emission of green house gases mathematically can be represented as a quadratic polynomial of generated power. To get more practical results, fuel cost function modified with the inclusion of valve point loading effect (B) and multiple fuel options (C).

2.1.1.1. Simplified economic cost function. Simplified economic dispatch problem can be represented as a quadratic fuel cost objective function as described in Eq. (1)

$$\mathrm{FT} = \sum_{i=1}^{n} F_i(P_i) \tag{1}$$

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2$$

where FT: total generating cost; F_i: cost function of ith generating unit; a_i, b_i, c_i: cost coefficients of generator i; P_i: power of generator i; n: number of generator.

2.1.1.2. Economic cost function with valve point loading effect. The generating units with multiple valves in steam turbines are available. The opening and closing of these valves are helpful to maintain the active power balance. However it adds the ripples in the cost function as shown in Fig. 1 which makes the objective function highly nonlinear. The sinusoidal functions are added to the quadratic cost function as given in (2)

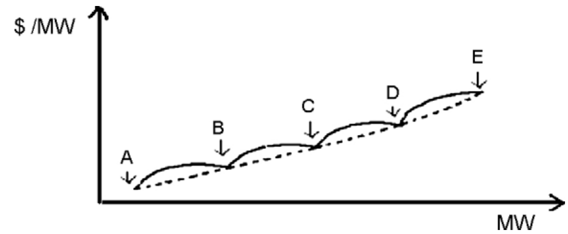

Fig. 1. Incremental fuel cost curve for 5 valve steam turbine unit.

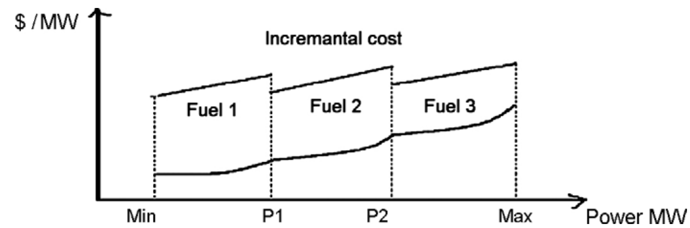

Fig. 2. Piecewise quadratic and incremental fuel cost function.

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2 + \mathrm{abs}(e_i \sin(f_i(P_{i\min} - P_i))) \tag{2}$$

where e_i and f_i are the coefficients of generator i considering valve point loading effect.

2.1.1.3. Economic cost function with multiple fuels. The different type of fuels can be used in thermal generating unit, hence fuel cost objective function can be represented with piecewise quadratic function reflecting the effect of fuel type changes.

$$\begin{aligned} F_i(P_i) &= a_i + b_i P_i + c_i P_i^2 && \text{if} \quad P_{i\mathrm{min}} \le P_i \le P_{i1} \\ &\quad a_i + b_i P_i + c_i P_i^2 && \text{if} \quad P_{i1} \le P_i \le P_{i2} \\ &\quad - && \quad - \\ &\quad - && \quad - \\ &\quad a_i + b_i P_i + c_i P_i^2 && \text{if} \quad P_{in-1} \le P_i \le P_{i\mathrm{max}} \end{aligned} \tag{3}$$

the nth power level (Fig. 2).

2.1.1.4. Emission function. The global warming is a concern for power industry, as it is accountable for the emission of green house gases in environment. As discussed earlier that amendment of clear air act and environmental friendly policies (Carbon Credit System) develops an interest of power sector towards reduction of emissions of NOx, SOx, CO_2 gases. Different mathematical formulation are used to represent the emission of green house gases in EMD problem. It can be represented in quadratic form [73,78,57], addition of quadratic polynomial with exponential terms [60,77,56], or addition of linear equation with exponential terms [88] of generated power.

$$E_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 \tag{4}$$

$$E_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 + \xi_i \exp(\lambda \times P_i) \tag{5}$$

$$E_i(P_i) = \alpha_i + \beta_i P_i + \gamma_i P_i^2 + \xi_{1i} \exp(\lambda_1 \times P_i) + \xi_{2i} \exp(\lambda_2 \times P_i) \tag{6}$$

where $\alpha_i, \beta_i, \gamma_i, \xi_{1i}, \lambda_1, \xi_{2i}, \lambda_2$ are the emission function coefficients.

2.1.2. Multi-objective problem formulation

The environmental awareness and deregulation in power sector necessitates to restructure the operation policies which accounts the emission aspects and individual profits as well. To accomplish

this, ED problem can be formulated as multi-objective problem with two or more competitive objectives. Various multi-objective ED problems reported in literature has combined economic emission dispatch (CEED) [44,60,45,77,56,57], maximize generation and irrigation [31], or minimize generation cost under different management structure [69], minimize pool purchase cost and emission [63], minimize cost and all pollutant gases [54], minimization of fuel cost—emission and real power loss [45], multi-area environmental economic dispatch MAEED [42,43]. To solve these conflicting objectives weighted sum [69] or price penalty factor approach [44] can used to convert into single objective function.

2.2. Equality and inequality constraints

(1) System power balance equation: it is an equality constraint which should be satisfied for hydrothermal system

$$\sum_{i=1}^{n} P_i + \sum_{j=1}^{m} P_j + P_{\text{loss}} = D_L \tag{7}$$

$$P_j = A_1 \times (X_j^2) + A_2 \times (U_j^2) + A_3 \times (X_j) \times (U_j) + A_4(X_j) + A_5 \times (U_j) + A_6$$

where P_i, P_j: power output from ith thermal unit and jth hydro plant. n, m: are the number of thermal and hydro generating unit in studied system; P_{loss}: transmission loss. D_L: load demand.

(2) Water balance equation:

$$X_j^t = X_j^{t-1} + Y_j^t - U_j^t - V_j^t + U_k^{t-\delta} + V_k^{t-\delta} \tag{8}$$

(3) Power generation limits:

$$P_{i\,\min} \le P_i \le P_{i\,\max} \tag{9}$$

$$P_{j\,\min} \le P_j \le P_{j\,\max} \tag{10}$$

$P_{i\text{ min}}$, $P_{i\text{ max}}$, $P_{j\text{ min}}$, $P_{j\text{ max}}$ are the minimum and maximum limits of generation for thermal and hydro plants.

(4) Reservoir storage limits:

$$X_{j\,\min} \le X_j \le X_{j\,\max} \tag{11}$$

$$X_{jo} = X_{j\,\text{initial}} \tag{12}$$

$$X_{jT} = X_{j\,\text{end}} \tag{13}$$

$X_{j\text{ min}}$, $X_{j\text{ max}}$, $X_{j\text{ initial}}$, $X_{j\text{ end}}$ are the minimum value of reservoir storage, maximum value of reservoir storage, reservoir storage at the starting of time horizon, reservoir storage at end of time horizon respectively.

(5) Hydro water discharge limits:

$$U_{j\,\min} \le U_j \le U_{j\,\max} \tag{14}$$

$U_{j\text{ min}}$, $U_{j\text{ max}}$ are the minimum and maximum discharge limit of hydro plants.

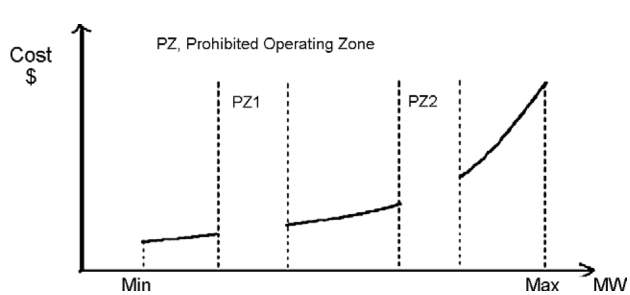

Fig. 3. Cost function with prohibited operating zone.

(6) Generator ramp rate limits:one of the impractical assumption has taken in conventional economic dispatch problem is that the adjustment of power output are instantaneous. But in practical circumstances ramp rate limit restricts the operation of all online units. The generation may decrease or increase within corresponding range so that the units are constrained due to the ramp rate limits as below

$$P_i - P_i^{t-1} \le UR_i$$
$$P_i^{t-1} - P_i \le DR_i$$

Modified generation limits after considering ramp rate limits are now given as

$$\max(P_{i\,\min}, UR_i - P_i) \le P_i \le \min(P_{i\,\max}, P_i^{t-1} - DR_i) \tag{15}$$

where UR_i, DR_i are the upward and downward ramp rate limit of generator.

(7) Prohibited operating zone:the generators may have certain range where operation is restricted due to the physical limitation of machine component, steam valve, vibration in shaft bearing etc. The consideration of prohibited operating zone creates a discontinuities in cost curve and convert the constraint as below.

$$\begin{aligned} P_i = P_{i\,\min} &\le P_i \le P_{i1}^L \\ P_{i,k-1}^U &\le P_i \le P_{i,k}^L \\ P_{i,zi}^U &\le P_i \le P_{i\,\max} \end{aligned} \tag{16}$$

where $P_{i,k}^L$, $P_{i,k}^U$ are the lower and upper boundary of kth prohibited operating zone of unit i, k is the index of prohibited operating zone, z_i is the number of prohibited operating zone (Fig. 3).

(8) Spinning reserve constraints:

$$\sum_{i=1}^{n} (\text{Min}(P_{i\,\max} - P_i, UR_i)) \ge S_R \tag{17}$$

S_R is the system spinning reserve requirement in MW.

(9) Line flow constraints:

$$|P_{fk}| \le P_{fk}^{\max} \tag{18}$$

where $P_{f,k}$ is the real power of line K and L is the number of transmission lines.

(10) Emission constraints:

$$Es \le L_{\text{SO}x},\ En \le L_{\text{NO}x},\ Ec \le L_{\text{CO}_2}$$

where Es, En, Ec are the SOx, NOx, CO_2 gases emission due to the combustion of fuel in thermal plants and $L_{\text{SO}x}$, $L_{\text{NO}x}$, L_{CO_2} are the maximum limits for emission of different gases.

3. Particle swarm optimization (PSO)

Particle swarm optimization is a population based stochastic search algorithm which is the most recent developments in the category combinatorial meta-heuristic optimization [68,74]. It was first introduced by Kennedy and Eberhart in 1995 [61] as new heuristic method. The original objective of their research was to graphically model the social behavior of bird flocks and fish schools. But this original version can only handle the nonlinear continuous optimization problems. Further advancement in this PSO algorithm can explore the global optimal solution of complex problems of engineering and sciences. Amongst various versions of PSO most familiar version was proposed by Shi and Eberhart [79]. The key attractive feature of PSO is its simplicity as it involves only two model Eqs. (19) and (20). In PSO, the co-ordinates of each particle represent a possible solution called particles associated with Position and velocity vector. At each iteration particle move

towards a optimum solution, through its present velocity, personal best solution obtained by themselves so far and global best solution obtained by all particles. In a physical d dimensional search space, the position and velocity of the particle i are represented as the vectors of $X_i = [X_{i1}, X_{i2}, \ldots, X_{id}]$ and $V_i = [V_{i1}, V_{i2}, \ldots, V_{id}]$ in the PSO algorithm. Let $P_{\text{besti}} = [X_{i1\text{pbest}}, X_{i2\text{pbest}}, \ldots, X_{id\text{pbest}}]$ and $G_{\text{best}} = (X_{1\text{gbest}}, X_{2\text{gbest}}, \ldots, X_{\text{ngbest}}]$ be the best position of particle i and its neighbors best position so far respectively. The modified velocity and position of each particle can be calculated using the current velocity and the distance from P_{besti} and G_{best} as follows:

$$V_i^{k+1} = K(V_i^k * \omega + C_1 * R_1 * (P\_\text{best}(i) - X_i^k) + C_2 * R_2 * (G\_\text{best} - X_i^k)) \tag{19}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{20}$$

$$K = \frac{2}{\text{abs}(2 - C - \text{sqrt}(C^2 - 4 * C))} \tag{21}$$

where V_i^k: velocity of particle i at iteration k; ω: inertia weight factor; C_1, C_2: acceleration coefficients; R_1, R_2: uniformly distributed random number between 0 and 1; position of X_i^k particle i at k iteration; P_best (i): best position of particle i until iteration k; G_best: best position of the group until iteration k; K: constriction factor.

In this velocity updating process, the value of the parameters such as ω, C_1, C_2, K should be determined in advance. The inertia weight ω is linearly decreasing as the iteration proceeds and obtained as

$$\omega = \omega_{\max} - \frac{(\omega_{\max} - \omega_{\min})\text{iter}}{\text{iter\_max}} \tag{22}$$

where $\omega_{\max}$: final inertia weight; $\omega_{\min}$: initial inertia weight; iter: current iteration number; iter_max: maximum iteration number.

4. Reviews for PSO in economic dispatch problem

The population based PSO has been considered as fast growing solution algorithm to solve the practical ED problem due to its simplicity. In PSO, movement of the particles are controlled by its previous own velocity and two acceleration components (cognitive component and social component). The high value of cognitive component compared to social component will result excessive wandering of particle through search space, whereas a relatively high value of social component may lead particles to rush prematurely towards a local solution. Cognitive and social component depends on PSO variants C_1, C_2, R_1, R_2. Similarly particles velocity on each dimension is clamped to a maximum velocity $V_{\max}$. Its high value facilitates global exploration and low value encourages local exploitation. Hence a concept of inertia weight ω is introduced by Shi and Eberhart [79] for better control between exploitation and exploration. The proper control of these variants (C_1, C_2, R_1, R_2, ω) can improve the performance of PSO. Many researchers suggested different modification in original PSO to keep a balance between local exploitation and global exploration to improve the solution quality with less computational time of such problem. The yearly (2003–2008) review of different research papers contributed in the field of application of PSO in different kind of ED problems are as follows.

Selvakumar et al. [44] solved the multi-objective CEED problem using PSO. Here two contradictory objectives (emission and economic cost) are combined by using penalty factor to form a single objective problem. Introduction of price penalty factor blends the emission cost with normal fuel costs.

Zhao et al. [45] used PSO with constriction factor and inertia weight (PSO-CF-IW) to solve the bid based dynamic ED in competitive electricity market. Objective function is to maximize the social profit which is a difference of benefit function of customer to cost function of generator. Paper includes power balance, generation bid quantities, customer bid quantities, ramp rate limits, line limit, and emission as equality and inequality constraints in optimization process.

Victorie and Jeyakumar [66] implemented a hybridized PSO with sequential quadratic programming (SQP) to solve ECD-VPL problem. In this paper real power balance, ramp rate limit, generation limit, voltage at load bus, transmission line constraints and spinning reserve are considered as constraints to problem. This method integrates PSO algorithm as the main optimizer with SQP as local optimizer to fine tune the solution region. In this firstly PSO is initialized to solve the problem and as better global best is found, the region is fine tuned using SQP by accepting this as initial searching point for the technique. It will help to explore the global optimal point at earlier iteration of PSO run.

Park et al. [62] adopted a modified PSO (MPSO) incorporating dynamic search space reduction strategy to accelerate the optimization of ECD-VPL and ECD-VPL-MF problems. This paper implemented a proper heuristic treatment mechanism to handle the equality constraints (power balance) and position adjustment strategy to handle the inequality constraints (generation limit) of ED problem, while each particle modifying its search point in PSO algorithm. In proposed method space reduction strategy is activated in case when the PSO performance is not improved during specified iteration number. In this case the search space is dynamically reduced as per the distance between the G_{best} and the minimum and maximum output of generator.

Umayal and Kamaraj [54] described PSO to solve the multi-objective combined emission economic dispatch problem. The paper formulated the multi-objective problem considering various competitive objectives fuel cost, NOx, SOx, CO_2, variation of generation mismatch. All objectives are weighted as per the importance and added together to form the final objective function. Unique feature of this paper is to introduce the inaccuracies and un-certainties in the hydrothermal schedule.

Bo et al. [78] proposed a multi-objective particle swarm optimization (MOPSO) to solve the ED problem. Here three objectives fuel cost, emission and real power loss have to minimize simultaneously with power balance, generation capacity and transmission line limit constraints. In proposed method two repositories (external memories) are maintained in addition to the search population. One of the global best individuals found so far by the search process, and one containing a single local best for each member of the swarm. Geographically based approach is used to get the different pareto optimal solutions. Finally fuzzy based mechanism with linear membership function is employed to select a best compromise solution from the tradeoff curve.

Park et al. [52] applied a chaotic particle swarm optimization for ECD-VPL problem subjected to active power balance and power generation limit constraints. Valve point loading effect consideration in ED problems make it more practical, however this increases the nonlinearity as well as the number of local optimal point in solution space. Chaotic logistic map based inertia weight variation in the velocity update equation avoids the premature convergence of PSO and helps to escape from local optimal point.

Jeyakumar et al. [39] describes a successful use of linearly decreasing inertia weight PSO (PSO-LVIW) to solve the multi-area economic dispatch (MAED), multi-fuel economic dispatch (PQCF), combined emission economic dispatch (CEED), economic dispatch with prohibited operating zone (ECD POZ). CEED is a multi-objective problem in which the objective is to minimize the fuel cost as well as emission of NOx. By using weight sum approach

both objectives are weighted as per importance and added together to produce a final objective function.

Chakraborti et al. [51] adopt PSO with linearly varying inertia weight with constriction factor (PSO-LVIW) to solve ECD-VPL problem. This paper considered few more constraints i.e., ramp rate limit, spinning reserve, network loss in addition to load balance, operating limits, ramp rate limits, network losses.

Yu et al. [35] proposed the global vision of particle swarm optimization with inertia weight (GWPSO), local vision of PSO with inertia weight (LWPSO), global vision PSO with constriction factor (GCPSO), local vision of PSO with constriction factor (LCPSO) for minimization of fuel cost subjected to power balance, hydro and thermal power generation limits, water balance equation, reservoir storage, discharge rate limit, begin and end storage limit. In GWPSO and GCPSO particles have information of entire group hence velocity update equation considers the global best value in social behavior, where as LWPSO and LCPSO have only their own information and its neighbors information, hence the local best value is used for the social term in this version of PSO. Neighborhood size can vary in even numbers. Simulation results shows that initially all versions are faster GCPSO, GWPSO slow down in later stage finally LCPSO, LWPSO provides the good result because of the huge ability to maintain the diversity of population.

Abido et al. [77] suggested the novel multi-objective PSO to solve the CEED problem subjected to generation limits and power balance constraints. Proposed approach extends the single objective PSO by proposing the new definitions of the local and global best individuals in multi-objective optimization problems. An average linkage based hierarchical clustering technique is also implemented to manage the pareto optimal set size and a fuzzy based mechanism is employed to extract the best compromise solution. Result shows that above method is able to produce multiple pareto optimal solution in one simulation run.

Lee et al. [58] used an iteration particle swarm optimization to minimize the addition of fuel and outage cost subjected to active power balance, power generation limit, spinning reserve, up and down time of generation unit, ramping speed. In proposed method an additional new index called iteration best (best value achieved by any particle in current iteration) is incorporated to control the movement of particle through velocity updating equation.

Titus and Jeyakumar [50] suggested an improved PSO to minimize the fuel cost along with startup and start down cost subjected to prohibited operating zone, hydro and thermal generation limit, water flow equation. A concept of craziness has been added in original PSO to provide the diversity, ergodicity, stochastic behavior in algorithm, to improve the solution quality with less time and avoid premature convergence.

Cohelo and Mariani [34] suggested a chaotic particle swarm optimization hybridized with implicit filtering technique to solve ECD-VPL problem subjected to power balance and generation limit constraints. This paper introduces a hanon chaotic mapping in PSO to improve the global convergence and implicit filtering technique to fine tune the chaotic PSO run in sequential manner. Proposed method is capable to escape from local minima point.

Jiejin et al. [38] proposed two versions of chaotic particle swarm optimization (CPSO) namely CPSO1 and CPSO2 to solve the ECD problem subjected to power balance, generation limits, ramp rate limits, prohibited operating zone and line flow limits. Proposed methods are the two phase iterative method in which PSO with Adaptive inertia weight factor (AIWF) is applied to perform the global exploration and further chaotic map local search is employed for local exploitation. Both CPSO1 and CPSO2 methods are similar, but they only differ in the mapping of decision variables into chaotic variables. In CPSO1 and CPSO2 Logistic map and tect mapping is used for local exploitation.

Selvakumar and Thanushkodi [41] adopted a new PSO (NPSO) to solve the three types of ED problem namely ED with prohibited operating zone (ED-POZ), ED with valve point loading (ECD-VPL), ED with valve point and multiple fuel option problems. Proposed method splits up the cognitive behavior into good experience component and bad experience component. Here particle remember its worst position along with its best position. NPSO is able to locate the promising area but fail to exploit the promising area to get good quality solution for complex multi-minima function, hence local random search is integrated with NPSO to explore the promising region.

Lee [46] proposed a multi-pass iteration PSO (MIPSO) to minimize the fuel cost along with startup cost subjected to power balance, generation limit, water discharge limit, water storage limit, ramp rate limit, spinning reserve, minimum up and down time, wind turbine generation percentage limit, generation limit of wind system. Conventional PSO suffers from low computational efficiency as the time horizon of scheduling increases, to solve such problems proposed method can improve the computation efficiency. MIPSO begins with random time stage and searching space and further refines the time interval between two time stages and the search spacing pass by pass (iteration). A new index of iteration best (Best amongst all particles in previous iteration) is also added to control the movement of particles.

Jayabarthi et al. [75] proposed a hybrid differential evolution (HDE) and particle swarm optimization method to solve the ECD problem. Objective function is formulated as to minimize the fuel cost subjected to active power balance, water discharge limit, reservoir storage limit, thermal and hydro generation limit, water balance equation. Both methods applied to the test system and it has been seen that although the optimal global solution is similar in case of HDE and PSO but the convergence rate is much smoother and faster in case of PSO.

Coelho and Lee [36] proposed a Chaotic and Gaussian based PSO to solve the ECD problem considering Prohibited operating zone, ramp rate limits, transmission loss, line slow constraints. This paper adopts a Gaussian or chaotic sequence random number generation between 0 and 1 for cognitive and social part of velocity update equation. Various versions of PSO includes Original PSO (PSO 1), Gaussian distribution in cognitive part and uniform distribution in social part (PSO 2), Gaussian distribution in social part and uniform distribution in cognitive part (PSO 3), Gaussian distribution in social and cognitive part (PSO 4), uniform distribution in cognitive part and logistic map Chaotic distribution in social part (PSO 5), logistic map chaotic distribution in cognitive part and uniform distribution in social part (PSO 6), Gaussian distribution in cognitive and Logistic chaotic distribution for Social part (PSO 7), logistic chaotic distribution for cognitive part and Gaussian distribution for social part (PSO 8). All versions of PSO are tested for 15 thermal unit systems and 20 thermal unit system and result shows that for 15 unit system PSO 4 and for 20 unit system PSO 3 provides good results.

Panigrahi et al. [53] described an adaptive particle swarm optimisation (APSO) technique to minimize the smooth (ECD) and non-smooth cost function (ECD-MF) incorporating transmission loss, prohibited operating zone, ramp rate limits, power balance, power generation limit. The proposed algorithm redefined with control on movement of particles in swarm and re-initialization of the population after specific iteration. The highly fitted particle will move slowly in comparison to the low fitted particle by simply assigning the inertia weight between $\omega_{\min}$ to $\omega_{\max}$ as per the rank of the particle in the swarm.

Chandrasekar et al. [40] used PSO with inertia weight and constriction factor (PSO-CF-IW) to minimize the fuel cost subjected to power balance, transmission loss, hydro generation limit, discharge limit, thermal and hydrogenation limit, water

balance equation. This paper considered the Hydro generation, thermal generation, discharge limits, reservoir volume as possible particles one by one in PSO algorithm. Results shows that the minimum cost is obtained when reservoir volume select as particle.

Selvakumar et al. [49] adopts the anti-predatory PSO to solve the ECD-VPL and ECD-VPL-MF problem. In proposed method PSO not only relies on foraging activity but also on anti-predatory activity. This paper introduces the new variants of PSO for the anti-predatory activity which helps the swarm to escape from predators. It splits the cognitive and social behavior of the particles into its good and worst experience. Inclusion of the worst experiences provides an additional exploration capacity to swarm.

Yuan et al. [47] suggested a enhanced particle swarm optimization (EPSO) to minimize fuel cost subjected to power balance, hydro and thermal generation limit, hydro discharge limit, reservoir storage volume, initial and terminal storage limit, water balance equation. In proposed method three additional features included in original PSO i.e., concept of repellor opposite to attractor (means particle learns from its worst position), chaotic logistic map random number generation, feasibility based rule to handle the equality and inequality constraints in scheduling problem.

Wang and Chanan [42] used linearly varying inertia weight PSO (PSO-LVIW) to solve the MAEED problem. In this objective is to dispatch the power among different areas by simultaneously minimizing the operational cost (fuel cost and transmission cost) and pollutant emission. Multi-objective PSO is used to solve this problem and pareto optimal solution are derived.

Wang and Chanan [43] adopted particle swarm optimization with local search to minimize the overall operational cost (fuel cost and transmission cost) of multi-area system with less emissions. As the problems formulated as MAEED problem with generation limits, area power balance, area spinning reserve, tie line constraints as equality and inequality constraints. In propose method after initialization of population, fitness value are calculated. Concept of pareto-dominance being applied to fitness value and non-dominated members stored in archive. Further fuzzy global best scheme is used to select the global best and synchronous particle local search (SPLS) is used to get the personal best values. Parallel niching and fitness process are also carried out to enhance the diversity of solutions. Update the velocity and position of particles using Eqs. (19) and (20). Turbulence factor (mutation operator), which is a random value between −1 and 1 is added to the updated position. It is helpful to prevent from stucking into local optimal solution.

Dobakhshari and Soroudi [55] discussed a hybrid gradient search PSO (HGPSO) method to solve the ECD-VPL, subjected to power balance, transmission loss, power generation limits. In this method parallel execution of GSM along with PSO make it possible to use the best results obtained by the gradient search as G_{best} for PSO.

Chuanwen and Etorre [48] suggested a self-adaptive chaotic particle swarm optimization is used to solve the ED problem in deregulated environment. Problem is formulated in which the maximization of generation profit is the objective function subjected to water balance equation, hydro generation limit, discharge rate, reservoir volume. This paper introduces logistic map chaotic sequence to generate the random numbers R_1, R_2 and self-adaptive inertia weight scale in original PSO to improve the performance.

Mandal et al. [59] adopts a PSO with inertia weight and constriction factor (PSO-IW-CF) to solve the ECD-VPL problem with power balance, water balance, hydro power and thermal generation limits, discharge limits, reservoir volume, initial and final reservoir limits.

Roy and Ghoshal [37] used a canonical PSO (CPSO), linearly decreasing inertia weight PSO, constriction factor PSO, velocity update relaxation momentum factor induced PSO (VURMFIPSO) and crazy PSO to solve the ECD-VPL problem. Sometime in bird flocking or fish schooling, a bird or fish suddenly change its movement direction. Proposed crazy PSO method introduces this natural behavior as craziness factor and modeled in the PSO algorithm to ensure that particle would have predefined craziness probability to maintain the diversity of the particles. This paper minimize the fuel cost with valve point loading effect as well as transmission loss subjected to active power balance, power generation limit and ramp rate limits. Proposed method validate for three types of objective functions first one have a_i, b_i, c_i all are positive (refers to conventional ECD problem), second one have a_i, b_i are positive but c_i is negative (refers to auction based load dispatch) and third one have a_i, b_i, are positive but some value of c_i are positive and some are negative (not reported so far).

Giang et al. [64,65] suggested an application of linearly decreasing inertia weight PSO to solve the ECD problem subjected to power balance, generation limit, ramp rate limits, prohibited operating zone, spinning reserve, line flow constraints. This paper directly adopts the generation power output of each unit as a gene, and many genes comprise an individual. Each individual within population represents a candidate solution for ECD problem. To select the personal best (P_{best}) and speed up the convergence of iteration procedure the evaluation value is normalized into the range between 0 and 1. Evaluation function is a reciprocal of fuel cost and power balance constraints.

Sriyaanyong [67] integrated traditional PSO with Gaussian mutation to solve the ECD-VPL problem. Inclusion of Gaussian mutation significantly enhances the diversity of swarm with good quality solution. Heuristic rules are also employed to modify the particles.

Alrashidi and Hawary [56] used PSO to solve the multi-objective CEED problem. In this paper novel techniques to handle the equality constraints are proposed. Using weight sum approach two objectives i.e., economic fuel cost and emission converted into single objective. Above two competitive objectives have assigned different weights and for each value of assigned weight PSO will provides a single solution in pareto optimal set.

5. Suggested modification in PSO for economic dispatch problem

PSO is a population based meta-heuristic optimization technique, in which the movement of the particles is governed by the two stochastic acceleration components (cognitive component and social component) and inertia component. All papers discussed in review section used a various versions of PSO. Few of them are listed as PSO with time varying inertia weight (PSO-TVIW), PSO with constriction factor (PSO-CF), PSO with Gaussian or chaotic based random number generation, introduction of craziness factor to increase the diversity of particle in PSO algorithm, integration of PSO with implicit filtering technique or direct search method or mutation operator and more. Although these methods are capable to provide the good quality results at faster rate, but when compared with other evolutionary optimization methods, their ability to fine tune the optimum solution is comparatively weak, mainly due to the lack of diversity at the end of search [PSO self-organizing-8]. Hence to increase the ability of global optimal solution at later stage, PSO with time varying acceleration coefficient (PSO-TVAC) [70], centroidal voronoi tessellation based initialization of swarm [80], active target particle swarm optimization (APSO) [81], exponential varying inertia weight

PSO [82], PSO combined with either Gaussian or sobol mutation [83,84], guaranteed convergence PSO (GCPSO) [87], self-adaptive PSO [72,85], introducing new metropolis coefficients as learning coefficients [86], PSO with division of work strategy (PSOwDOW) [71] can be used.

6. Conclusions

The environmental friendly policies, competition amongst power generating companies, fast emerging difference between demand and supply, develops a requisite for proper operation policies for power generating companies. It can be accomplished only when a proper mathematical formulation of ED problem should be there and all practical constraints are taken into account. Particle swarm optimization has paid a lot of attention for solution of such problems, as it will not suffer from stuck into local optimal solution, dependability on initial variables, premature and slow convergence and curse of dimensionality. In comparison to conventional optimization techniques, PSO has given an improved results within less computational time. This paper summarized the work reported in literature in the field of economic dispatch using PSO, but still further improvement in PSO algorithms are required, as present versions of PSO have slower convergence at later stage and also not able to provide optimal solution for real time scheduling problems.

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